Moderator and shielding layout for the new UCN source

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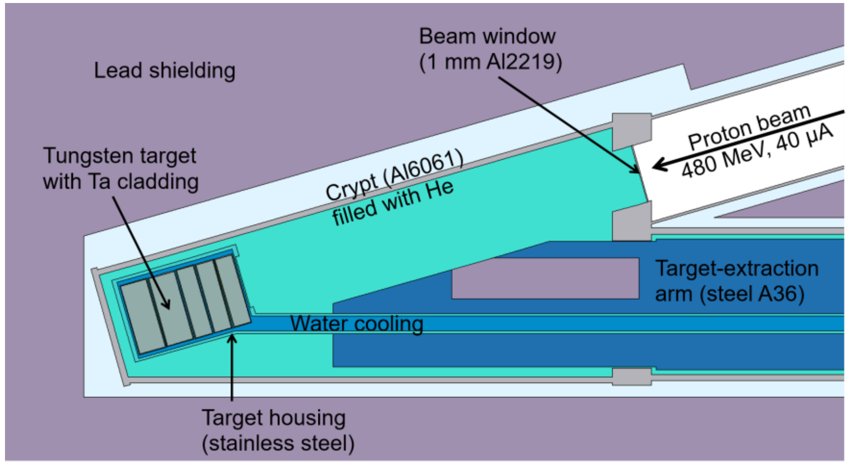
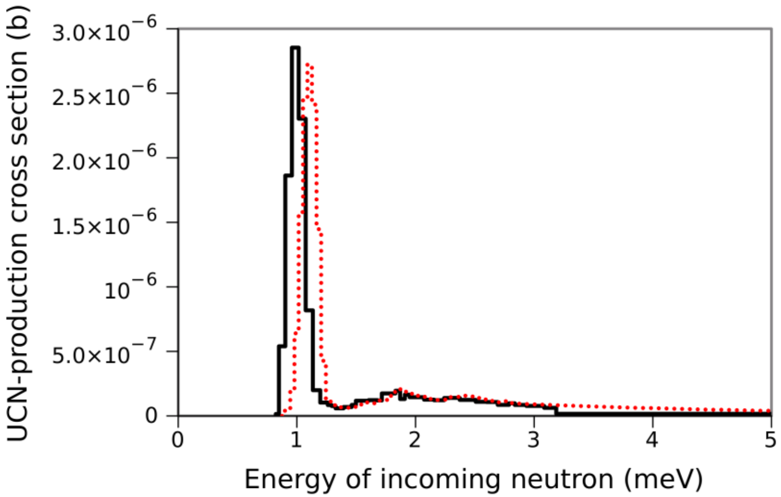
Moderator optimization for next-generation UCN source

Goal

- Maximize UCN density in nEDM cell $\rho = \frac{P\tau}{V}$
- Neglects transport losses (independent of moderator geometry)
- $\tau^{-1} = \tau_{\mathrm{He}}{}^{-1} + \tau_{\mathrm{wall}}{}^{-1} + \tau_{\beta}{}^{-1}$
- $V = V_{\mathrm{src}} + V_{\mathrm{guide}} + V_{\mathrm{nEDM}}$
- $\tau_{\mathrm{He}} \sim Q^{-1}$, if V constant ρ approximately proportional to $\frac{P}{Q}$

UCN production P

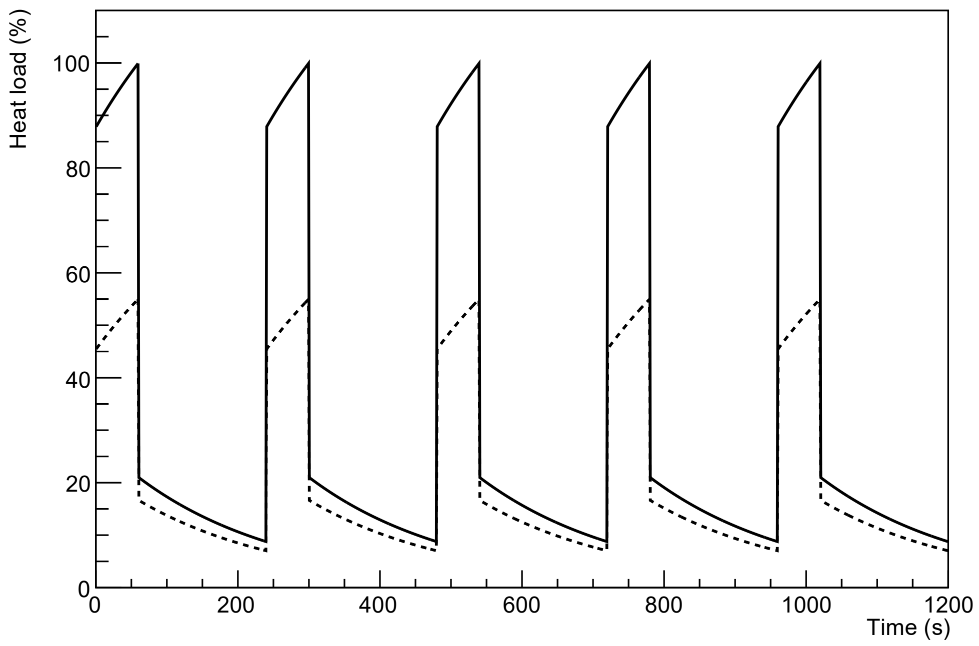




Simulated with MCNP

- Detailed target model
- Secondary neutrons, gammas, electrons
- UCN production cross sections [1], [2]

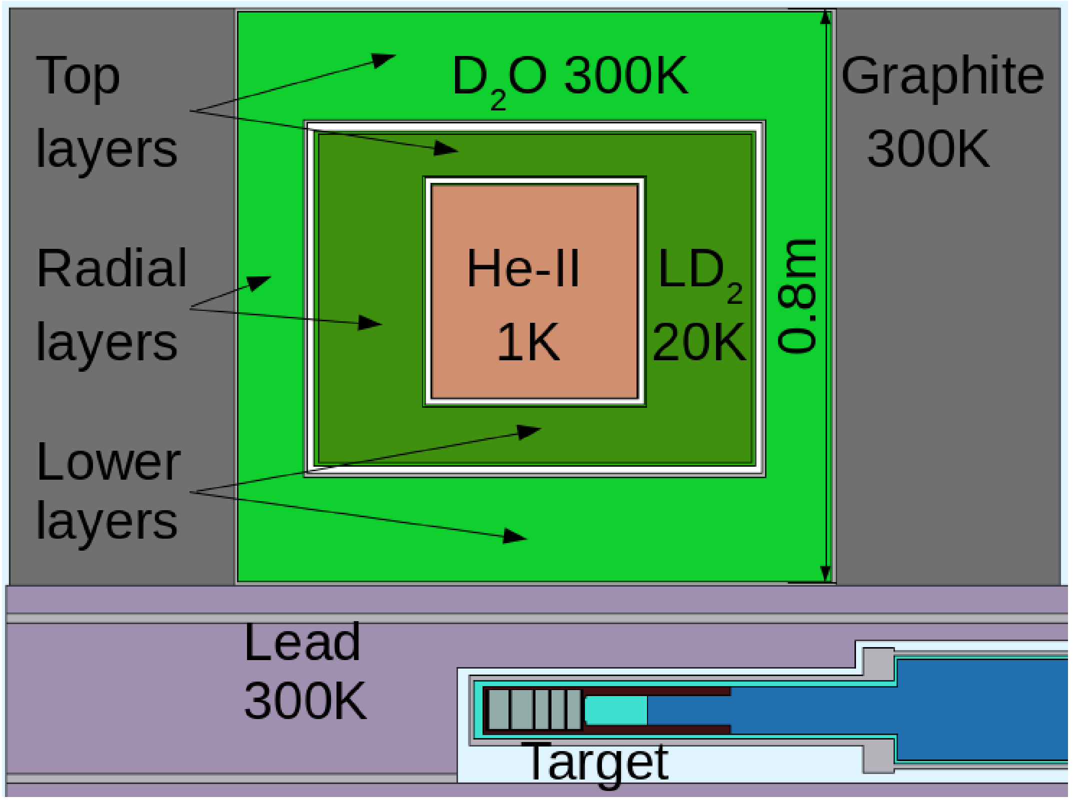
Heat load Q



Prompt + decay heating

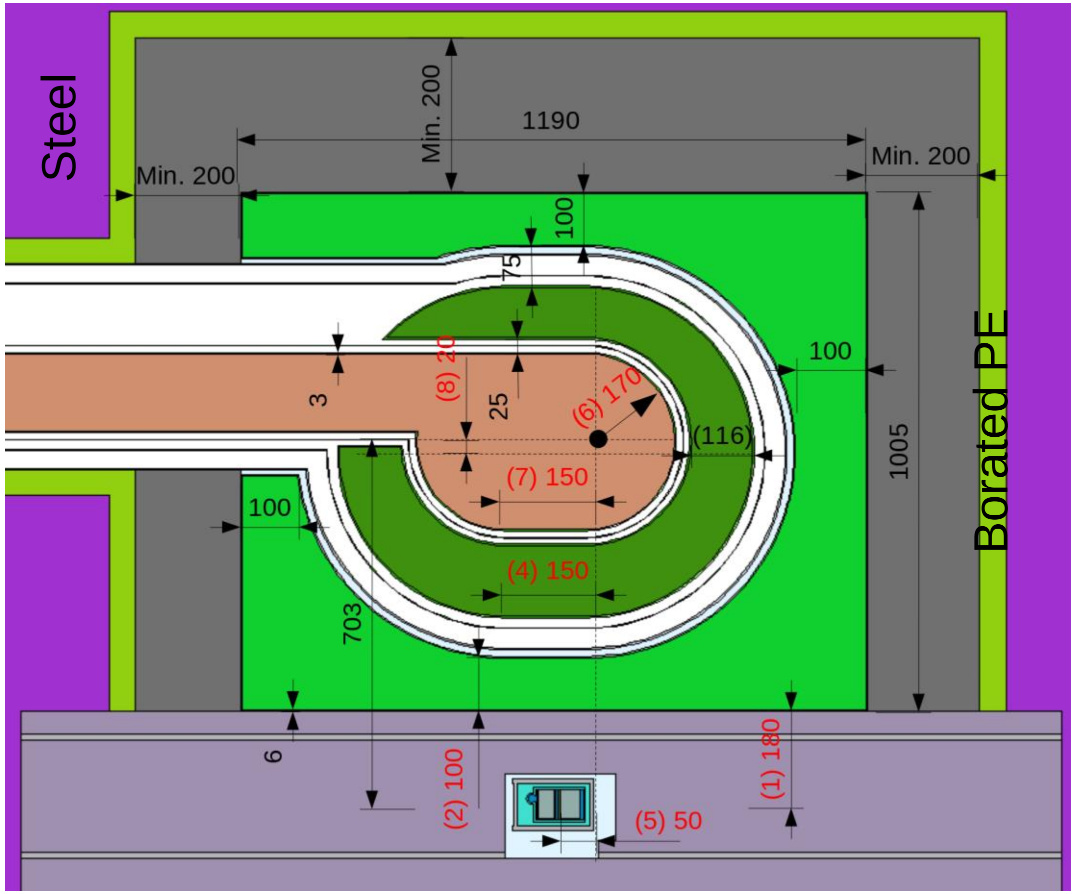
- MCNP energy-deposition tallies
- Heat removed by 2m-long, 15cm-wide channel through 4He-3He heat exchanger
- ${\tau_{\mathrm{He}}}^{-1} = 0.008\ \frac{1}{sK^7}\ T^7$
- Gorter-Mellink + vanSciver/HePak
- Kapitza resistance with k_G = 20 – 40
- $\tau_{\mathrm{He}} = 500{\sim}1500\ \mathrm{s} \cdot \left(\frac{Q}{1\ W}\right)^{-1.5\sim-1.0}$

Initial basic geometry



- Optimized individual layer thicknesses with constant He-II volume

Multidimensional optimization



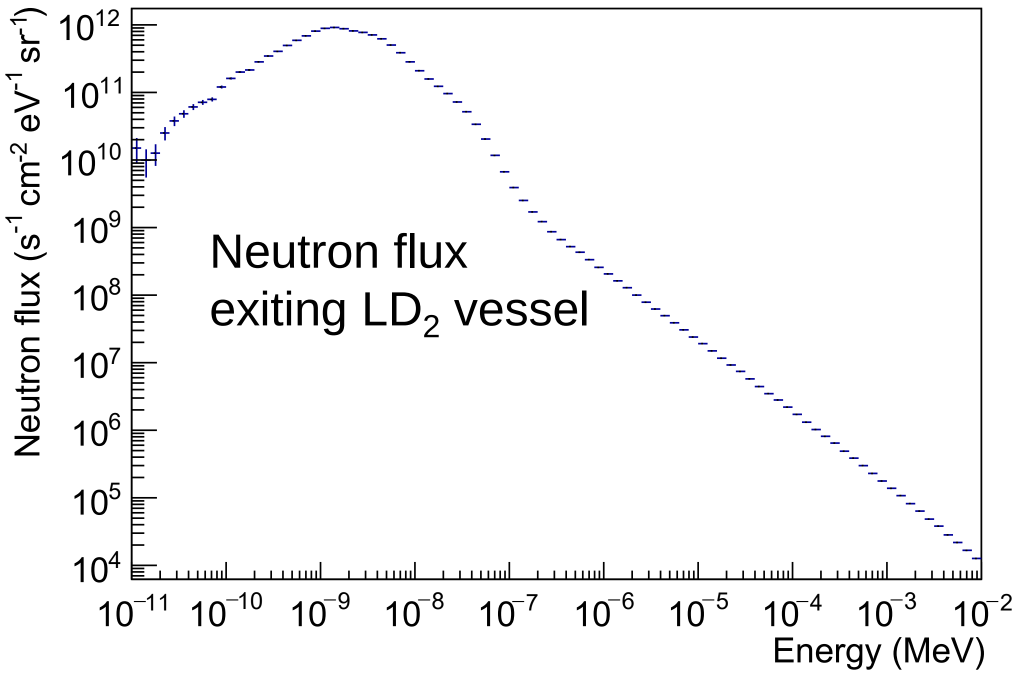
- More realistic geometry
  - Added UCN guide
  - All vessels Al6061
  - Thermal shields and vacuum vessels
  - Wall thicknesses from first stress calcs
- Full optimization of all layers, including He-II volume
- Optimized for wide range of assumptions

Parameter	Range
τ_{wall}	60 s – 100 s
τ_β	880 s
B	500 s – 1500 s
a	-1.5 – -1.0
$V_{\text{guides}} + V_{\text{EDM}}$	100 L – 200 L

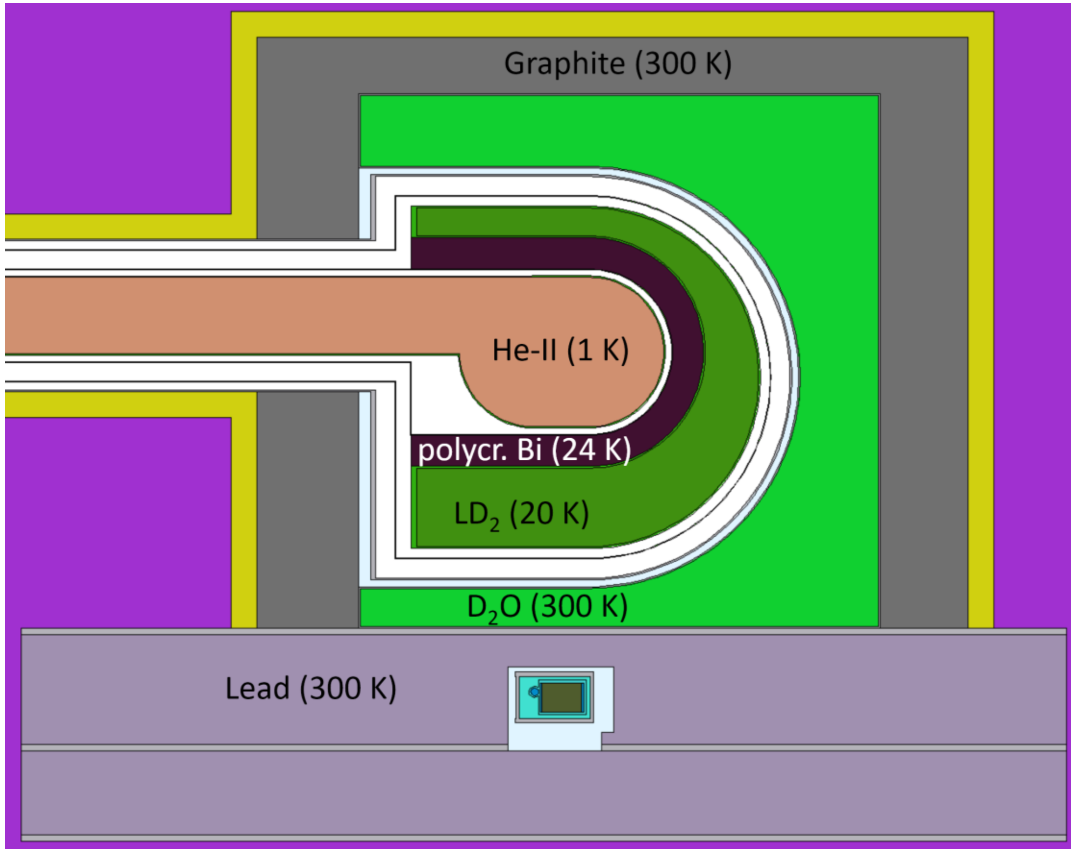
Results

Volume (L)	
UCN converter (w/o guide)	**34.2**
Liquid deuterium	**125**
Heavy water	804
UCN production (s^{-1})	$\mathbf{21.5 \cdot 10^6}$
Max. heat load (W)	
UCN converter	4.4
Converter vessel	5.2
Converter total	**9.6**
Liquid deuterium	21
Deuterium vessel	17
Deuterium total	**38**
Heavy water	320
Heavy-water vessel	36
Vacuum separator	7.8
Thermal shield	13
Vacuum vessel	14
Heat exchanger	0.072
^{3}He	0.024
Tritium production (MBq/d)	
Liquid deuterium	330
Heavy water	828
^{3}He	29

- After 8 months of operation at 40 μA and 25% duty cycle



Studied variatons



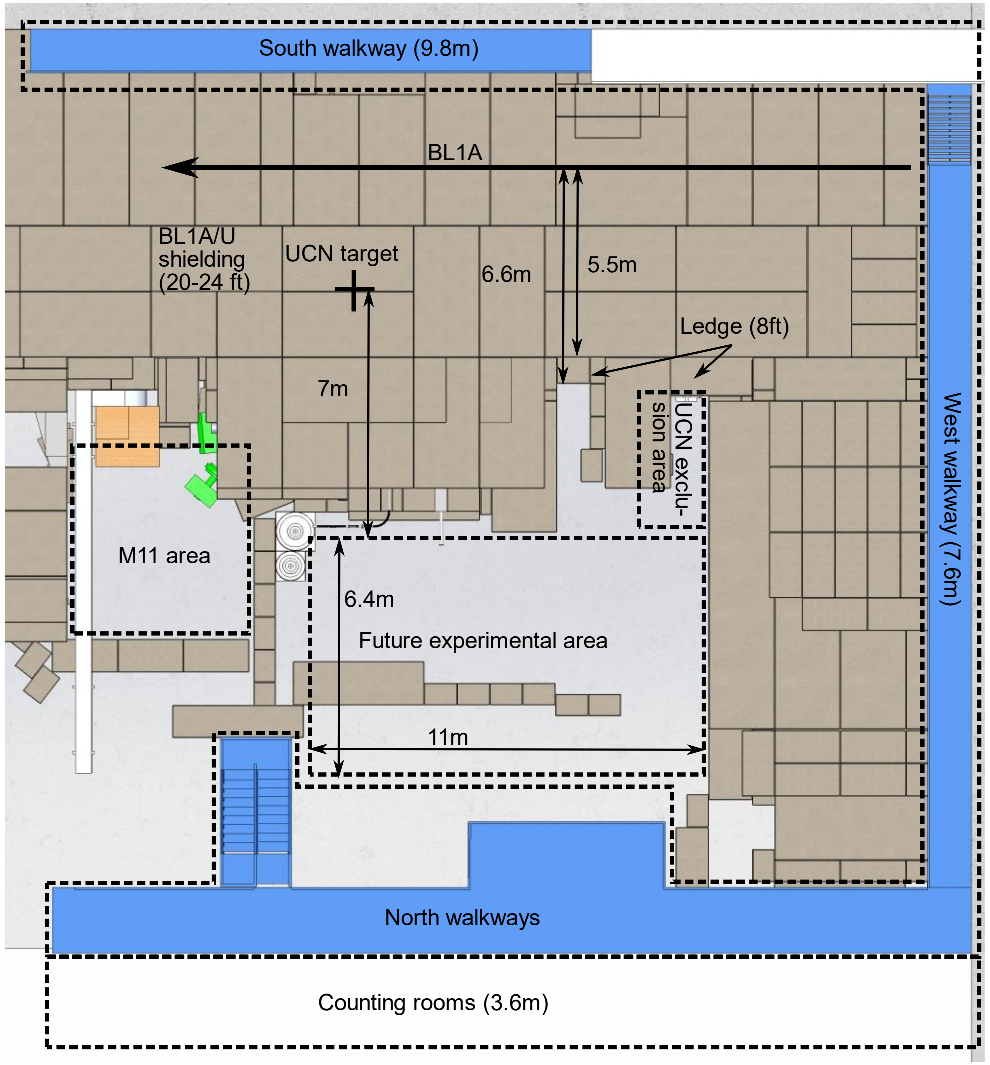
- Converter vessel materials
  - Pure beryllium best
  - BeAl and MgAl alloys good
- Liquid deuterium
  - Density/temperature changes UCN density <5%
  - Effect of para-deuterium max. -7%
  - -4% per 1% hydrogen (commercial purity >99.8%)
- VCN guide (5x5 cm^2) penetrating D_2O has no effect
- Bi neutron filter
  - +25% UCN density
  - +200% heat load at 20K
  - x10 activation
- Optimization for other cold moderators
  - Solid D_2O: -60% UCN density
  - Liquid hydrogen: -66% UCN density

Important parameters and recommendations

Improvement	Estimated increase in UCN density in EDM cell
Beryllium converter vessel	100 %
AlBeMet or AZ80 converter vessel	30 % – 50 %
Thinner converter vessel	25 % per millimeter
Increased LD_2 volume	5 % per 15 L
Thinner vacuum separator/LD_2 vessel	5 % per millimeter
Thinner thermal shield/D_2O vessel	2.5 % per millimeter
Reduced spacing around converter	5 % per centimeter

- Geometry robust against ~1cm changes in moderator thicknesses
- Best improvements:
  - Use alternative materials for He-II bottle
  - Minimize wall thicknesses and spacings
  - Increase LD_2 volume
- Design note has been released on TRIUMF Docushare and Plone

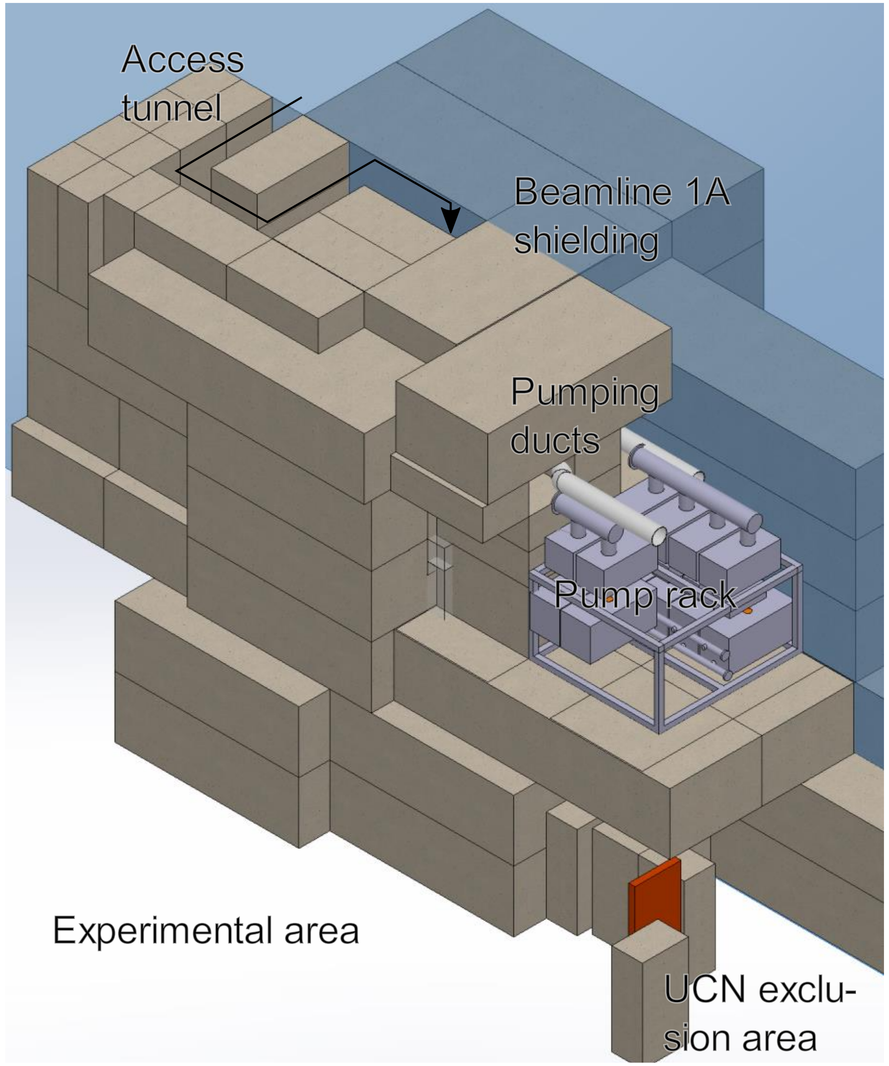
Radiation shielding for next-generation UCN source



Requirements

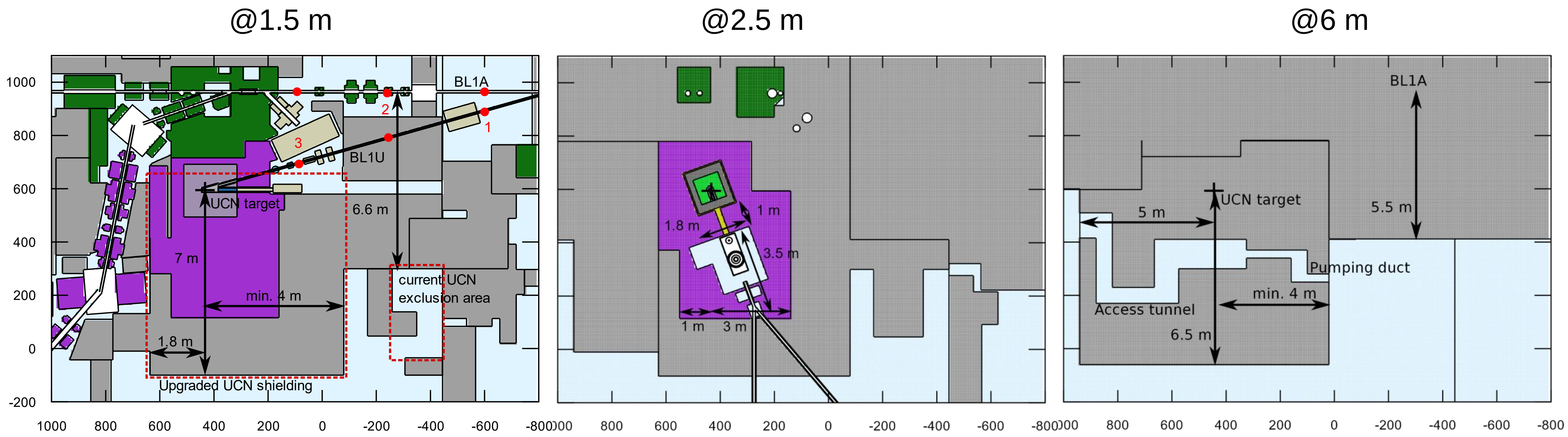
- < 0.5 μSv/h in uncontrolled high-occupancy areas (counting rooms)
- < 10 μSv/h in uncontrolled low-occupancy areas (exp. area, walkways)
- < 100 μSv/h in controlled low-occupancy areas (M11 area?)
- Quick access to cryostat through tunnel, while beamline 1A operating
- < 65 μSv/h for maintenance at cryostat lid

Shielding concept

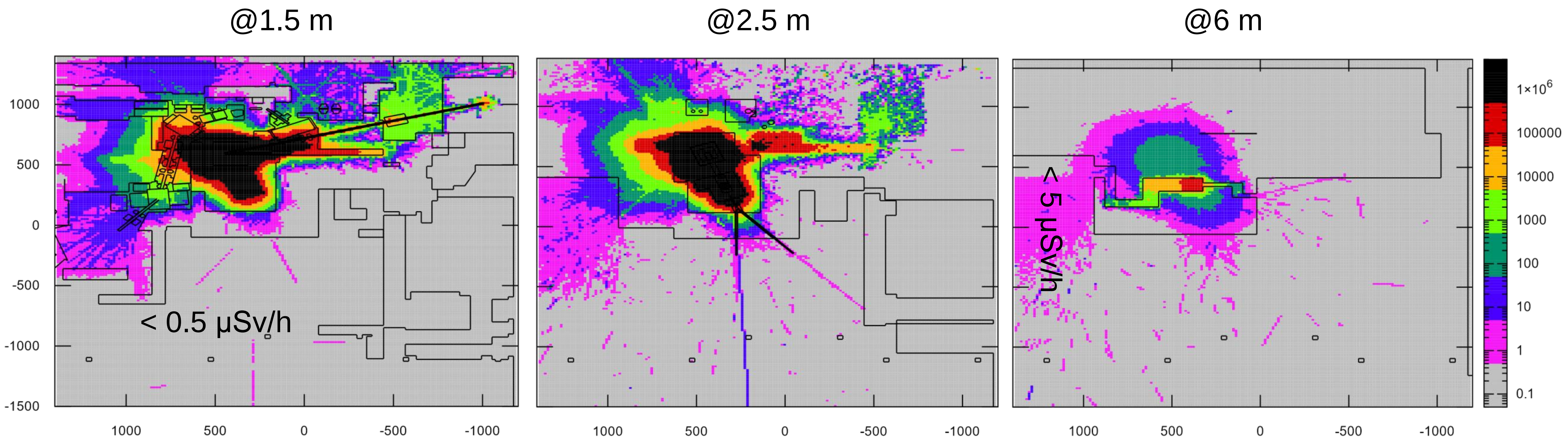


- Custom steel shielding around moderators & cryostat

Fluka simulation model



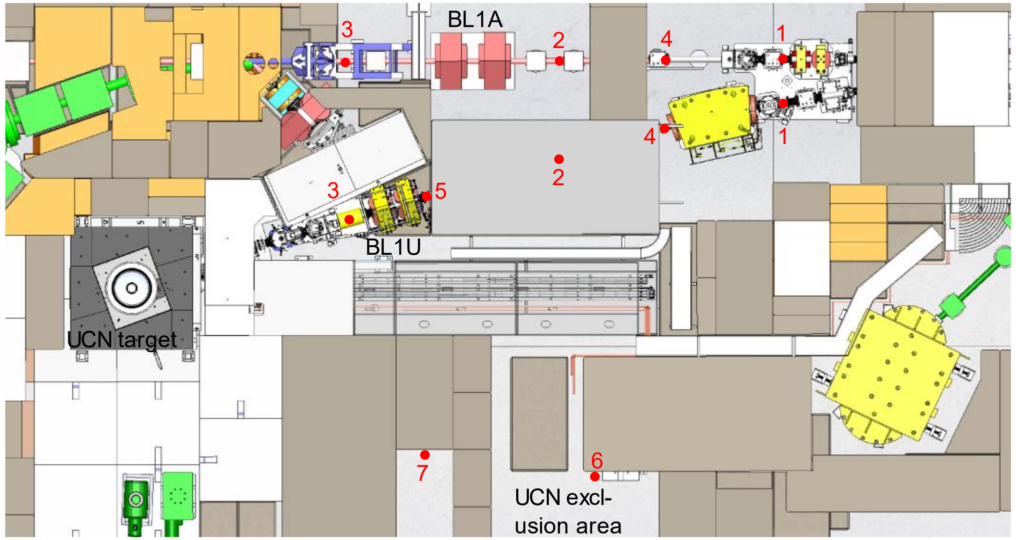
Fluka simulation results – UCN target irradiated



Fluka simulation results

Nominal operation

- UCN target irradiated with 40 µA
  - Exp. area, walkways, counting rooms safe
  - M11 area up to 50 µSv/h (is exclusion area)
- T1 target irradiated with 140 µA
  - Cryostat pit safe < 5 µSv/h



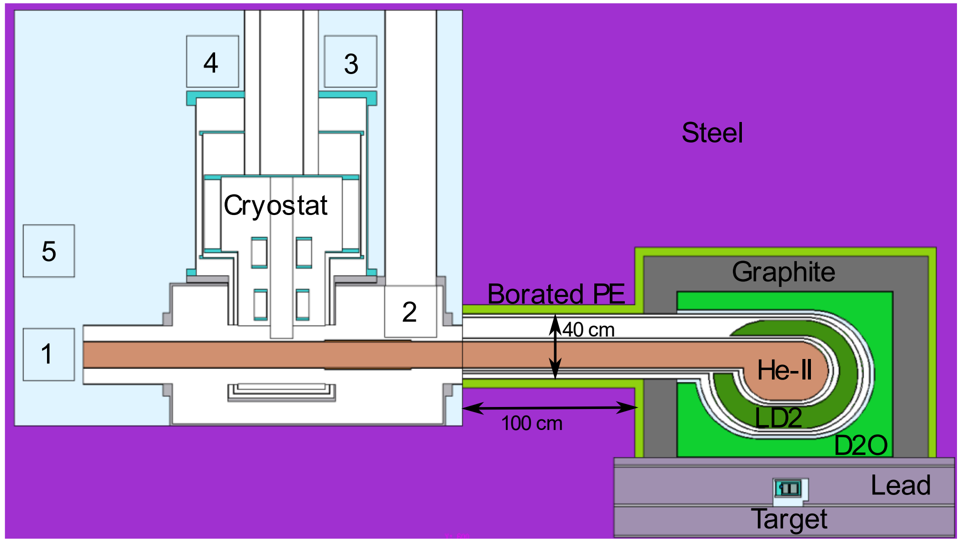
Accidental beam losses

- Max. allowed beam (140 µA in 1A, 40 µA in 1U) dumped into beam pipe
- All simulated scenarios contained with slight modification of BL1A shielding (exclude access tunnel at floor level)
- Compared with empirical Moyer model

Loss at	Dose at	d (m)	θ (°)	t_{conc} (m)	t_{iron} (m)	Dose (mSv/h) Moyer	Fluka
BL1A #1	#6	6.9	73	3.8	0	41	20 ± 2
BL1A #4	#6	6.6	90	3.6	0	28	-
BL1A #2	#7	6.3	58	4.3	0	35	2 ± 0.2
BL1A #3	#7	6.2	100	2.2	0.8	11	0.2 ± 0.2
BL1U #1	#6	6.6	45	4.6	0	9.2	100 ± 3
BL1U #4	#6	5.5	74	3.6	0	28	-
BL1U #2	#7	4.9	60	3.6	0	78	20 ± 1
BL1U #5	#7	3.9	74	2.37	0	1050	-
BL1U #3	#7	3.7	90	2.2	0	720	10 ± 3

Dose in cryostat pit

Prompt dose

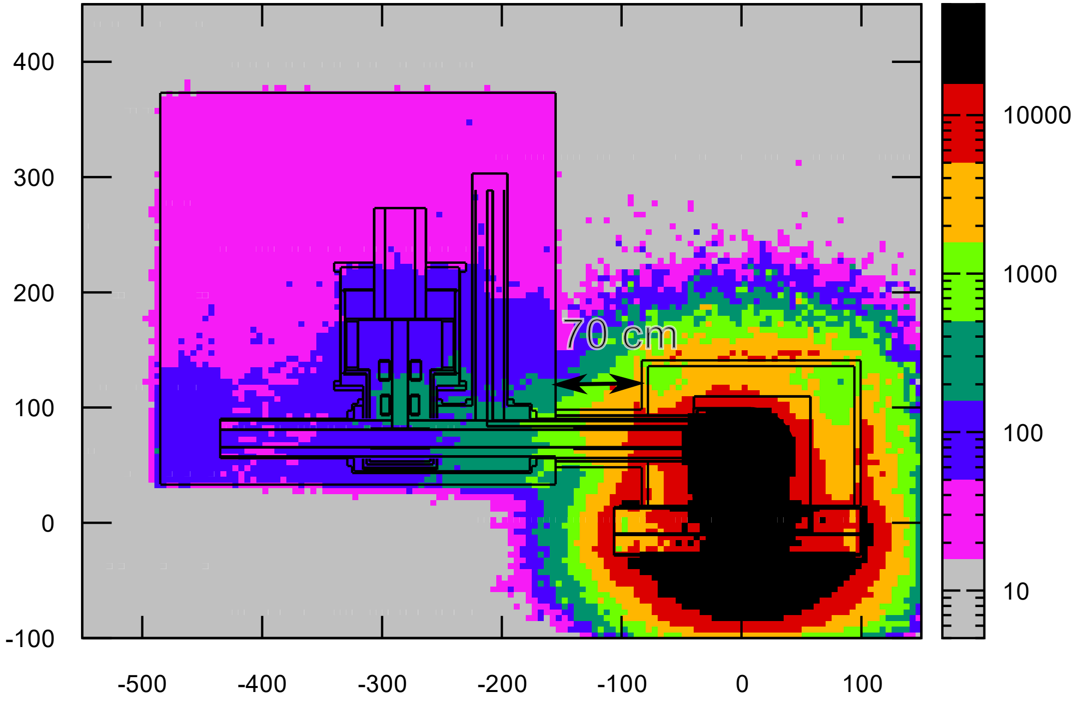


Dose absorbed by H/C/N/O/F compounds

- Max. 10 Gy/h (@2)
- 1-2 Gy/h (@1,5)
- <0.2 Gy/h (@3,4)

Residual dose

Dose rate after 28d (uSv/h)



Residual dose at cryostat lid <65 µSv/h (1 day after shutdown)

100 µSv @0.5m from guide (after 4weeks)

Status

Shielding concept

- Can probably fulfill all requirements
- Design note ready for formal review
- Detailed design will follow
  - Exact size of cryostat pit?
  - Maximize experimental area
  - Minimize shine from shield penetrations
- How to control access to cryostat?
  - Procedural or engineered lockout?
  - Confined space
  - Access while cold? Oxygen deprivation!

Moderator optimization

- Finished, design note released [1] [2]
- Reduce reflectors to improve shielding?
- Continue to implement changes during detailed design

Thank you!